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Combustion Practice for Control of Organic Emissions from Municipal Waste-to-Energy Plants

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COMBUSTION PRACTICE FOR CONTROL OF ORGANIC EMISSIONS FROM MUNICIPAL WASTE-TO-ENERGY PLANTS

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16. ABSTRACT The paper summarizes studies sponsored by the EPA to assess combustion practice that can be used to minimize trace organic emissions. Although this study was concerned primarily with defining good combustion practice that will minimize the emission of toxic congeners of dioxin and furans, the relationship of combustion conditions to furnace emission of other pollutants (e.g., particulates, heavy metals, NOx, CO, and other organics) was also considered. Recent advances in municipal waste combustion control techniques were defined by discussions with most of the major incinerator designers in the U.S. and Europe. Combustion control strategies to minimize organic emissions were then formulated using knowledge concerning the formation and destruction of organics and the best state-of-the-art engineering techniques for achieving good combustion. These strategies were developed for three types of combustion systems: mass burn, starved air, and refuse derived fuel. The strategies involve three major elements: design criteria for good combustion, validation of design and performance objectives during start-up, and continuous monitoring and control of the combustion process during operation. Components of each element of the good combustion practices are defined, and the limitations of generalized strategies for good combustion are discussed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Carbon Monoxide	Pollution Control	13B
Wastes	Incinerators	Stationary Sources	14G
Combustion	Toxicity	Waste-to-Energy Plants	21B 06T
Organic Compounds	Hydrocarbons	Municipal Waste	07C
Furans	Heterocyclic Compounds	Dioxin	
Particles		Particulate	
Nitrogen Oxides		Heavy Metals	07B

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ABSTRACT

Many U.S. municipalities who are confronted with mounting solid waste disposal problems associated with landfilling are turning to incineration. Combustion significantly reduces the volume of wastes and the liberated heat can be converted to heat or electric power to provide revenue. A major concern related to the proliferation of waste-to-energy plants is the potentially deleterious health and environment effects associated with emission of trace quantities of hazardous organics such as polychlorinated dioxins and furans. This paper summarizes studies sponsored by EPA to assess combustion practice which can be used to minimize trace organic emissions. Although this study was primarily concerned with defining good combustion practice which will minimize the emission of toxic congeners of dioxin and furans, the relationship of combustion conditions to the furnace emission of other pollutants such as particulate matter, heavy metals, NO_x, carbon monoxide, and other organics was also considered. Recent advances in municipal waste combustion control techniques were defined by discussions with most of the major incinerator designers in the United States and Europe. Combustion control strategies to minimize organic emissions were then formulated using knowledge concerning the formation and destruction of organics and the best state-of-the-art engineering techniques for achieving good combustion. These strategies were developed for three types of combustion systems: mass burn, starved air, and refuse derived fuel. The strategies involve three major elements: design criteria for good combustion; validation of design and performance objectives during start-up; and continuous monitoring and control of the combustion process during operation. The components of each element of the good combustion practices are defined, and the limitations of generalized strategies for good combustion are discussed.

INTRODUCTION

Many U.S. municipalities who are confronted with mounting solid waste problems associated with landfilling are turning to incineration. Some estimates indicate that the amount of waste being burned will increase by a factor of three by 1990[1]. One major concern that stems from the proliferation of waste-to-energy plants is emissions of trace amounts of potentially toxic organic compounds. Of particular concern and interest to the public is the presence of polychlorinated dibenzo(p)dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs).

The U.S. Environmental Protection Agency (EPA) has evaluated emissions from three classes of municipal waste combustors (MWCs): mass burning incinerators, refuse derived fuel (RDF) combustors, and modular incinerators. Tests on MWCs have indicated emission levels of total dioxins and furans (PCDD/PCDF) ranging from less than 1 to greater than 20,000 ng/Nm^3, depending on the combustion technology and flue gas cleaning technology employed[1]. Older designs and some types of combustors have been found to have emissions as much as four orders of magnitude higher than those from modern mass burn systems[2-5]. Thus, even though modern municipal waste combustors can be designed and operated with very low emissions of trace organics, they can also be improperly designed and operated giving rise to higher emission levels.

A study was undertaken for the EPA to identify combustion strategies which would minimize the emission of trace organics from municipal waste-to-energy facilities. The study concentrated on defining what specific combustion control techniques are currently being used by system designers and operators that have successfully resulted in lower emissions. The approach followed involved a state-of-the-art review of engineering techniques via

detailed and comprehensive discussions with most of the major incinerator designers in the United States and Europe. The information gained from system designers and operators was then combined with engineering systems analysis and theoretical considerations on trace organic formation and destruction in order to define combustion control strategies for trace organics. Although this study was primarily concerned with defining good combustion practice which will minimize the emissions of toxic congeners of dioxins and furans, the relationship to the furnace emission of other pollutants, such as particulate matter, heavy metals, nitrogen oxides (NO_x), carbon monoxide (CO), and other organics, was also considered.

This paper describes the theoretical rationale for the combustion strategy which resulted from the EPA study. More details of the results of the state-of-the-art review and the recommended combustion practice can be found elsewhere[6]. It should be noted that the proposed combustion strategy represents an initial attempt to develop such a strategy. It has not been verified and must necessarily be modified as the data base is expanded. A number of follow-up studies have been initiated to more completely investigate the validity of the recommended combustion practice and to evaluate the ability to retrofit existing systems to these practices.

TRACE ORGANIC EMISSIONS AND CONTROL

Several mechanisms for the formation of PCDD and PCDF in municipal waste combustion systems have been proposed by researchers. The potential sources of PCDD that have been identified include the following general mechanisms:

- Trace PCDD/PCDF material in the municipal waste which is not destroyed in the combustion zone
- Synthesis of PCDD/PCDF in the fuel rich zones of the furnace and failure to destroy before leaving the furnace

- Unburned organic precursors of dioxin in the lower furnace which subsequently react to form PCDD/PCDF
- Synthesis of unburned organic precursors which catalytically react at low temperatures to form PCDD/PCDF in the presence of fly ash

It is clear that regardless of which of the mechanisms is active, the key concern is the escape of organics from the combustion zone of the furnace. Either the precursors to dioxin or dioxin itself must be destroyed within the furnace. Thus, the combustion strategy involves the control of all the organics synthesized as combustion intermediates and unburned material. Combustion strategies can be developed around the simple principle of minimizing the emissions of all organics from the furnace.

The strategy for minimizing the emission of trace organics is based upon a desire to provide an environment which will ensure the destruction of effectively all gaseous organic species. This suitable environment requires the presence of oxygen at a sufficiently high temperature. Furthermore, it is necessary that, to the extent possible, all combustion gases experience the same environment. Thus, mixing is important because it will ensure uniform temperatures and composition. Mixing should be rapid as well as complete, in order to maximize residence times for destruction of organics in the higher temperature zones before significant heat removal has occurred. The attainment of the appropriate temperatures will depend upon the balance between heat released and heat absorbed. All of the above will maximize solids burnout and combustion efficiency. Exhaust CO concentration is a good measure of combustion efficiency because high levels of CO are normally associated with poor air/fuel mixing.

The simplistic view of combustion optimization as the "three Ts" (time, temperature, and turbulence) is not directly valid in this context. For

example, as will be discussed further in the next section, the gas-phase residence time should not be considered solely as a necessary reaction time, but rather as a mixing time. Time is required for air and intermediates to mix but, once mixed at sufficient temperature, the gas-phase destruction reactions take place virtually instantaneously. There is no need to hold the mixed gases at this temperature for a longer time to destroy trace organics. However time is required to complete the combustion of solid-phase particles which have been carried from the bed into the furnace gases. Further, turbulence on its own is not sufficient to ensure the necessary mixing. Two separate highly turbulent stream tubes in the furnace will not mix despite their high turbulence level unless they contact each other. Thus, mixing of the furnace gases with air requires that the turbulent air jets be dispersed throughout the combustion gases. Finally, the definition of a mean temperature is inappropriate. The trace species that escape the furnace may experience temperature pathways significantly different from the mean temperature level. Concepts based strictly on mean times above temperatures (such as qualifying maximum volumetric heat release rates) do not treat the low temperature pathways which exist in all municipal waste combustors.

It is thus postulated that good combustion conditions will minimize the furnace emission of all organics which can result in the emission of PCDD/PCDF and other potentially hazardous organic pollutants. The difficulty arises in defining criteria for good combustion which will be applicable to all incinerators or MWC systems. The vendors and manufacturers who have developed and who supply MWC systems often take distinctly different design and operating approaches to meet the same overall objective: the combustion of municipal solid waste (MSW) in a thermally efficient and cost-effective manner. A

partial listing of some of the major manufacturers who provide MWC systems is given in Table 1. The basic design and operating conditions for MWC systems offered by these manufacturers are described in the EER report on the combustion control of organic emissions[6].

Four classes of MWC systems were defined in the EPA study on the control of organic emissions from MWC: Mass Burning Incinerators, Refuse Derived Fuel (RDF) Combustors, Modular Multistage Incinerators, and Fluidized Bed Combustors. Recommendations for good combustion practice (GCP) were developed for the first three classes. Insufficient information was available to develop recommendations for fluid bed combustion systems.

The development of recommendations for GCP involved three different elements, each with a number of subelements or components. These elements include design, operation/control, and verification. The design of the combustion system must be consistent with the objectives of ensuring that the temperature, oxygen concentrations, and mixing within the combustor are consistent with minimum formation of precursor organics and the maximum destruction of organic compounds. Operation/control is necessary to ensure that the system functions in a manner consistent with the design goals and that appropriate steps are taken to ensure that the combustion system is constrained to operate within the established operating envelope. Verification refers to the continuous monitoring of combustion process conditions and furnace/stack emission parameters to ensure continuous operation within the defined design/operating envelope.

The recommendations for good combustion practices in mass burn, RDF combustors, and modular starved-air incinerators are presented in Tables 2, 3, and 4, respectively. Important features of the recommended combustion practices are summarized in the following sections.

TABLE 1. Some of the major MWC system manufacturers

EUROPEAN MANUFACTURERS	AMERICAN MANUFACTURERS
VOLUND (DENMARK)	SIGNAL ENVIRONMENTAL
DEUTSCHE BABCOCK (GERMANY)	OGDEN-MARTIN
STEINMUELLER (GERMANY)	RILEY STOKER / TAKUMA
MARTIN (GERMANY)	COMBUSTION ENGINEERING
VON ROLL (SWITZERLAND)	C-E / DeBARTOLOMEIS
WIDMER AND ERNST (SWITZERLAND)	DETROIT STOKER
	WESTINGHOUSE / O'CONNOR
	FOSTER WHEELER
	BABCOCK & WILCOX
	SYNERGY
	CONSUMAT
	BASIC ENGINEERING
	ENERCON/VICON

TABLE 2. GOOD COMBUSTION PRACTICES FOR MINIMIZING TRACE ORGANIC EMISSIONS FROM MASS-BURN MUNICIPAL WASTE COMBUSTORS

Element	Component	Recommendations
Design	Temperature at fully mixed height	980°C (1800°F) at fully mixed height
	Underfire air control	At least 4 separately adjustable plenums. One each under the drying and burnout zones and at least two separately adjustable plenums under the burning zone
	Overfire air capacity (not an operating requirement)	40% of total air
	Overfire air injector design	That required for penetration and coverage of furnace cross-section
	Auxiliary fuel capacity	That required to meet start-up temperature and 980°C (1800°F) criteria under part-load operations
Operation/ Control	Excess air	6-12% oxygen in flue gas (dry basis)
	Turndown restrictions	80-110% of design - lower limit may be extended with verification tests
	Start-up procedures	On auxiliary fuel to design temperature
	Use of auxiliary fuel	On prolonged high CO or low furnace temperature
Verification	Oxygen in flue gas	6-12% dry basis
	CO in flue gas	50 ppm on 4 hour average - corrected to 12% CO_2
	Furnace temperature	Minimum of 980°C (1800°F) (mean) at fully mixed height across furnace
	Adequate air distribution	Verification Tests (see text Chapters 8 and 9 in Reference 6)

TABLE 3. GOOD COMBUSTION PRACTICES FOR MINIMIZING TRACE ORGANIC EMISSIONS FROM RDF COMBUSTORS

Element	Component	Recommendations
Design	Temperature at fully mixed height	980°C (1800°F) at fully mixed height
	Underfire air control	As required to provide uniform bed burning stoichiometry (see text)
	Overfire air capacity (not necessary operation)	40% of total air
	Overfire air injector design	That required for penetration and coverage of furnace cross-section
	Auxiliary fuel capacity	That required to meet start-up temperature and 980°C (1800°F) criteria under part-load operations
Operation/ Control	Excess air	3-9% oxygen in flue gas (dry basis)
	Turndown restrictions	80-110% of design - lower limit may be extended with verification tests
	Start-up procedures	On auxiliary fuel to design temperature
	Use of auxiliary fuel	On prolonged high CO or low furnace temperature
Verification	Oxygen in flue gas	3-9% dry basis
	CO in flue gas	50 ppm on 4 hour average - corrected to 12% CO_2
	Furnace temperature	Minimum of 980°C (1800°F) (mean) at fully mixed height
	Adequate air distribution	Verification Tests (see text Chapters 8 and 9 in Reference 6)

TABLE 4. GOOD COMBUSTION PRACTICES FOR MINIMIZING TRACE ORGANIC EMISSIONS FROM STARVED-AIR COMBUSTORS

Element	Component	Recommendations
Design	Temperature at fully mixed height	980°C (1800°F) at fully mixed height
	Overfire air capacity	80% of total air
	Overfire air injector design	That required for penetration and coverage of furnace cross-section
	Auxiliary fuel capacity	That required to meet start-up temperature and 980°C (1800°F) criteria under part-load conditions
Operation/ Control	Excess air	6-12% oxygen in flue gas (dry basis)
	Turndown restrictions	80-110% of design - lower limit may be extended with verification tests
	Start-up procedures	On auxiliary fuel to design temperature
	Use of auxiliary fuel	On prolonged high CO or low furnace temperature
Verification	Oxygen in flue gas	6-12% dry basis
	CO in flue gas	50 ppm on 4 hour average - corrected to 12% CO_2
	Furnace temperature	Minimum of 980°C (1800°F) at fully mixed plane (in secondary chamber)
	Adequate air distribution	Verification Tests (see text Chapters 8 and 9 in Reference 6)

Temperature

There is a broad distribution of temperatures within a municipal waste combustor that make mean conditions difficult to define. Figure 1 shows temperature profiles in the Steinmueller mass-burn combustor at Stapelfeld, West Germany, for both full and partial (60 percent) load operation. Mean times at temperature defined by maximum volumetric heat release rates do not characterize conditions in the furnace adequately. Three-dimensional heat transfer, flow, and combustion models are generally required to predict, even crudely, the temperatures experienced by the combustion gases. The Steinmueller data indicate that a greater than 200°C (360°F) temperature variation exists across any plane in the mid-portion of the furnace. The typical temperature variation is from 1000°C (1832°F) at near center-line to 800°C (1472°F) near the walls. At low loads the temperatures are generally lower [peak 900°C (1652°F)] and the distribution is skewed due to changes in flow and combustion conditions.

Ensuring that furnace emission of organics such as PCDDs/PCDFs are minimized from municipal waste combustors requires a knowledge of minimum temperature pathways. The formation mechanisms of PCDDs and PCDFs are extremely difficult to define, reflecting the complexity of the reactions that occur during the combustion of refuse. The critical step necessary to prevent emissions of the intermediate organics is to ensure that the minimum temperature experienced by the organics, after they have mixed with oxygen, is sufficient for their rapid destruction. Thus, it is not the mean temperature that must be defined, but the minimum temperature experienced by the combustion gases.

Combustion control of organics requires that the combustion gases are mixed with oxygen. Only in the presence of oxygen are the reactions, which complete the combustion of organics to harmless species such as CO_2 and H_2O, rapid. The requirements for ensuring adequate mixing are therefore at least

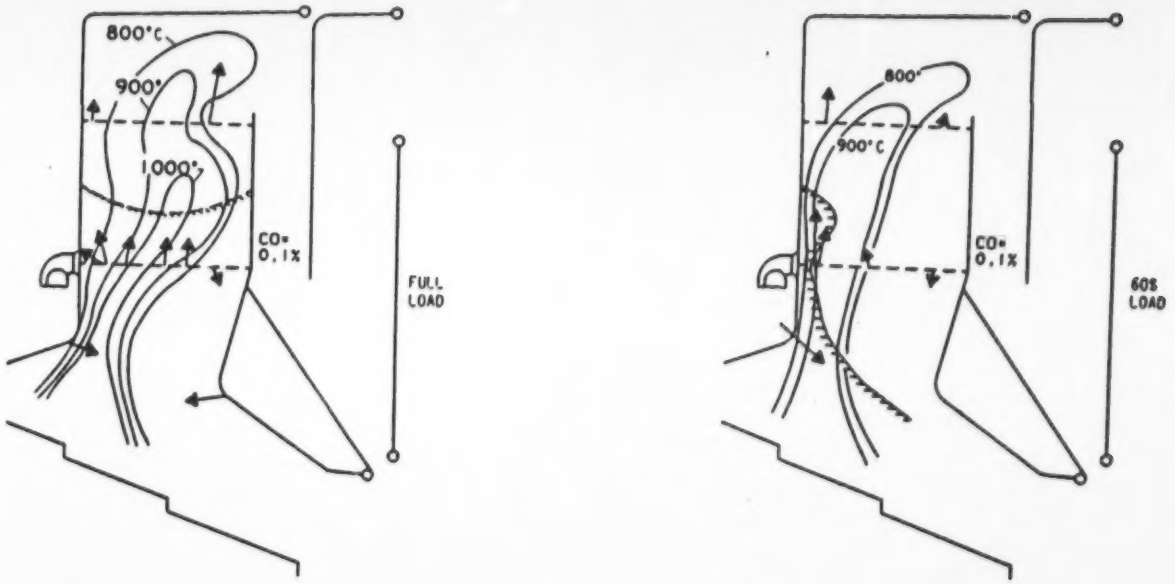

Figure 1. Temperature distributions in an operating mass-burn combustor (Reference 7).

as important as the temperature criteria. The mixing requirements for combustion air are discussed in the subsequent sections.

Municipal waste combustion systems may be characterized by defining a mean temperature at some location in the radiant section. Using that characterization approach, the mean temperature must be high enough to ensure that the minimum temperature is sufficient to destroy organic species. The location chosen for the characteristic temperature is also important. The current evaluation has selected that location as the "fully mixed height" - the point beyond the final air addition location where complete mixing should have occurred. In mass burn, waterwall designs, and RDF fired systems, overfire air jets are used above the grate region to mix air with the gases leaving the burning refuse bed. For most systems, with good engineering practice for overfire jet design, the fully mixed height should be on the order of 1 m (or less) above or downstream of the last overfire jet. For less traditional systems, such as the Westinghouse/O'Connor combustor, the fully mixed height might be in the radiant furnace just above the rotary portion interface with the stationary furnace wall (assuming that there is no additional overfire air addition). For the Volund system the fully mixed height would be above the refractory arch after final air injection and after the split flows have merged. For other non-traditional designs, the fully mixed height should be defined based on the consideration of the last air injection point and the mixing characteristics of the air introduction scheme.

A mean temperature must be defined which ensures that the minimum temperature at the fully mixed height is sufficient to destroy PCDDs/PCDFs and their precursors. Figure 2 is an illustration of the conditions that exist in a mass-burn combustor. At the fully mixed height above the overfire air jets, there is a distribution of temperatures, as shown by the hypothetical cross-sectional isothermals. With good grate and overfire air jet design, the range

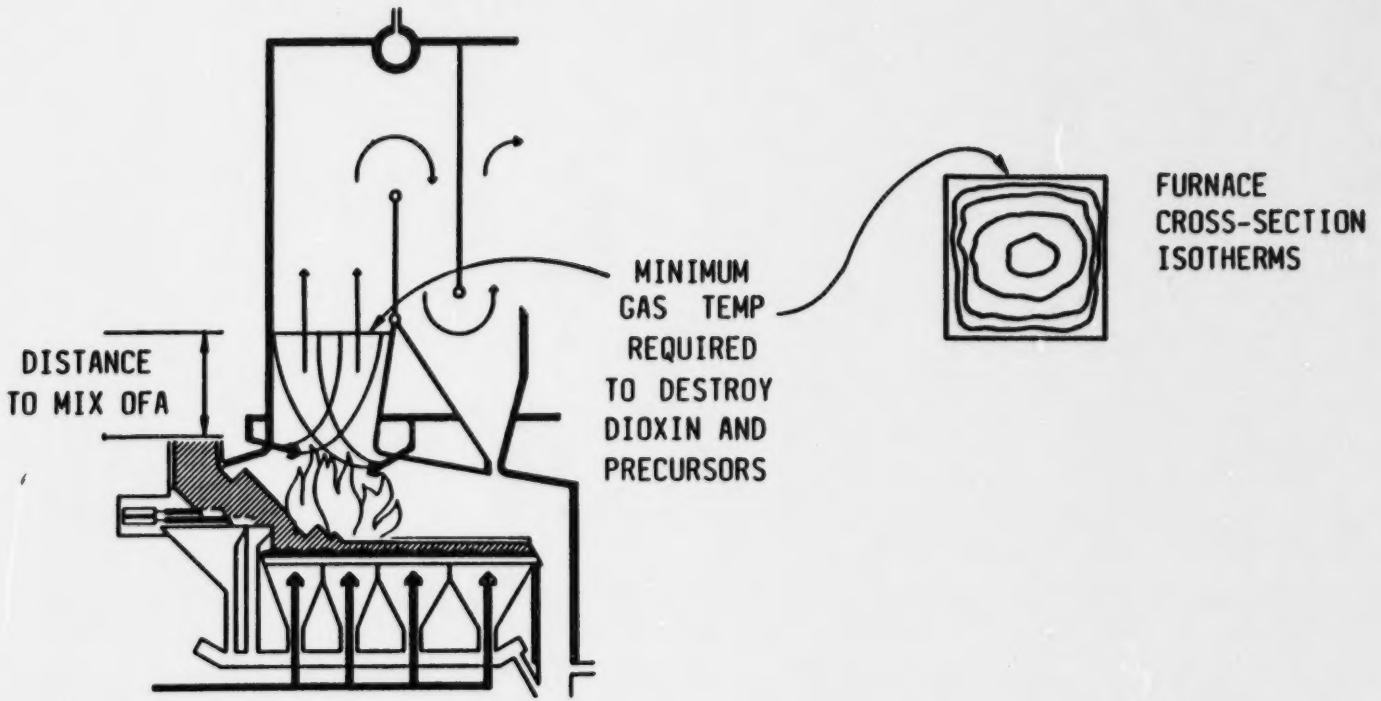

Figure 2. Required temperature for destruction of intermediate organics.

of temperatures will be kept to a minimum. However, a 200°C (360°F) temperature variation could still exist at this plane (e.g., see Figure 1). Thus, a mean temperature must be selected such that the minimum temperature is greater than the thermal decomposition temperature required to fully destroy intermediate hydrocarbons.

The thermal decomposition data obtained by University of Dayton Research Institute (UDRI)[8] can be used as the basis for indicating the temperature which will be required to destroy organics. Figure 3 provides some of the reference data for a range of organic intermediates including unchlorinated dioxins and furans, benzene, and chlorinated hydrocarbons. Unchlorinated dioxin/furan species are generally unstable above 700°C (1300°F), although potential precursors such as chlorophenols are stable to 815°C (1500°F). Hexachlorobenzene is one of the most stable species; it does not totally decompose below 900°C (1650°F) although such species (totally chlorinated organics) are unlikely candidates as PCDD and PCDF precursors. A temperature of 980°C (1800°F), which is quite often associated with municipal waste combustion requirements, is roughly 65°C (150°F) above the thermal decomposition temperatures of the most stable hydrocarbon intermediates. Thus a mean temperature of 980°C (1800°F) at the fully mixed height should be adequate to ensure that the minimum temperature is sufficient to destroy the most thermally stable hydrocarbons at very short residence times. In particular, such a design guideline is adequate for PCDD and PCDF species along with their potential precursors, such as chlorophenols.

It is possible to demonstrate the adequacy of a particular design by calculating the mean temperature at the mixed height using simple heat transfer relationships for the boiler. It is recommended that these calculations be performed with the design oxygen levels and refuse combustion characteristics assuming clean waterwalls. The use of clean walls is recognized to be conservative since the existence of an ash layer will increase the resistance

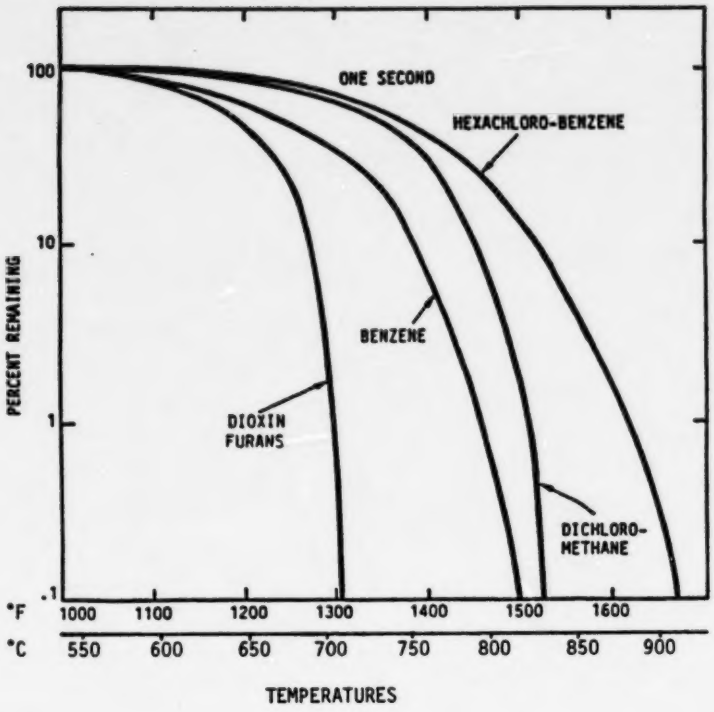

Figure 3. Thermal decomposition characteristics of selected hydrocarbons (Reference 8).

to heat transfer and therefore raise furnace gas temperatures; however, the characteristics of the layer cannot be an accurately defined priority. Experimental data could also be used to more accurately establish the mean temperature at the fully mixed height.

Combustion Air

An excess of combustion air is essential for the complete oxidation of combustible material. Combustion will not be completed, and harmful intermediate species may form and escape the furnace if oxygen is not provided in sufficient quantity at the appropriate location. Four factors concerning combustion air are important:

- The total amount of air
- The distribution of primary air
- The distribution of overfire air
- The verification of appropriate air distribution

Each of these aspects associated with combustion air will be discussed in the following subsections.

Total Air Requirements

The first aspect involves the amount of total combustion air which is necessary for complete combustion. There can be too much air or too little air. With too little air, the furnace will be oxygen-starved either throughout the furnace or in localized zones. The total air flow must be sufficient (1) to ensure that no localized zones are oxygen-deficient, and (2) to dampen surges due to excessively volatile refuse. In other words, there must be sufficient excess oxygen available to dampen out spatial and temporal

variations in fuel composition to avoid the possibility of oxygendeficient zones. On the other hand, too much air can excessively cool the furnace. Adiabatic flame temperatures (see Figure 4) are hottest at stoichiometric (zero percent excess oxygen) conditions and fall off with increasing excess air due to the dilution of furnace gases with air that must be heated.

The range of excess air that is appropriate can be established based upon current practice and experience. Mass-burn waterwall systems have been found to operate best with flue gas oxygen levels between 6 and 12 percent. Operation with less than 6 percent may be acceptable for certain situations such as extremely well-mixed mass-burn systems. It is reported that the Westinghouse/O'Connor system and the Enercon/Vicon systems operate at lower excess air levels and still achieve relatively low trace organic emissions. Similar levels (6-12 percent) are current practice for small modular two-stage systems. These excess oxygen levels correspond to excess air levels of between 40 and 100 percent. RDF-fired systems are typically designed to operate at lower excess air levels, taking advantage of the reduced variability in fuel characteristics.

Primary Air Requirements

The second aspect relating to combustion air is the proper distribution of primary or underfire air. For mass-burn and RDF systems, primary air is introduced through the grate and into the bed of burning refuse. For multistage systems, the primary air is introduced to the first zone. The key requirement for the primary air system is to get the primary air to where burning is taking place in the refuse bed.

For mass-burn grate systems, the primary air should be introduced through a number of separately controllable plenums underneath the grate. In current

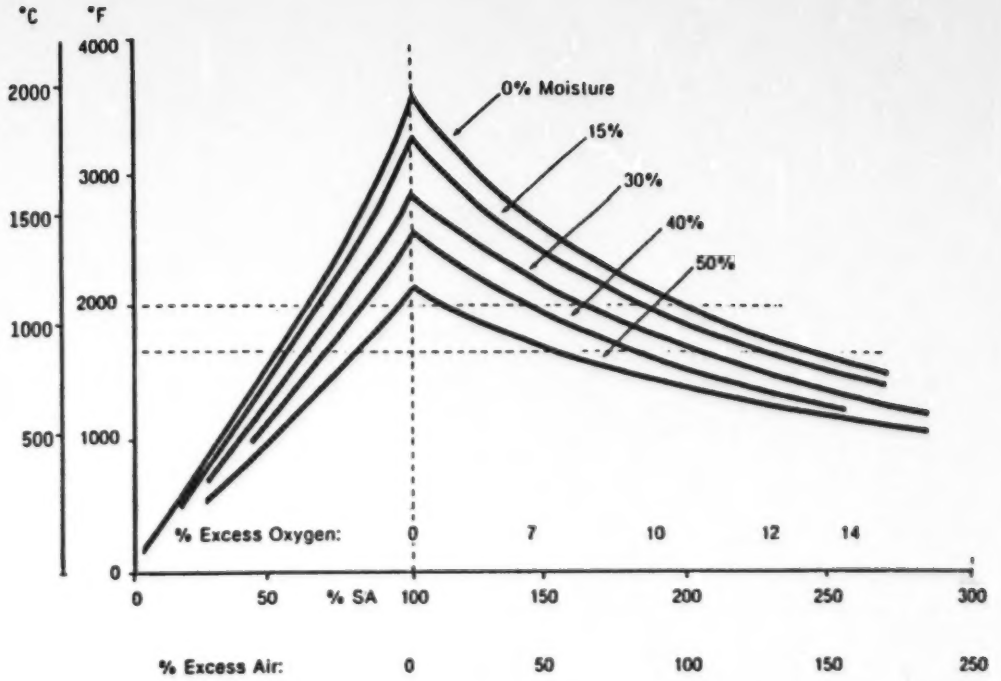

Figure 4. Theoretical temperature of the products of combustion, calculated from typical MSW properties, as a function of refuse moisture and excess air or oxygen (from Reference 9). Reproduced with permission ASME.

practice, between four and six primary air control regions are employed along the grate in order to have the capability of distributing the air to the active burning zones. A high pressure drop across the grate is desirable to ensure that the bed region supplied by each plenum is completely covered with air and there is minimal bypassing around thicker regions of refuse.

Both the quantity and the distribution of underfire air are important parameters. The quantity of underfire air will directly impact the burning rate of the MSW on the system grate or hearth. Therefore, the quantity of underfire air - along with grate speed - may be used as a quick response trim parameter for the steam production rate. Over long averaging times, the steaming rate is obviously controlled by the MSW feed rate, while the quantity and distribution of undergrate air will control (1) the location of MSW burnout, and (2) the mass averaged excess air of combustion products leaving the lower furnace. Generally, the distribution of underfire air should be such that good carbon burnout is achieved and the main flame is concentrated on the burning grates. Air flows to the drying and finishing grates are generally minimized, consistent with moisture content in the fuel and low organic content in the bottom ash.

For RDF-fired spreader-stoker units, primary air should be introduced through the traveling grate to correspond to the distribution of RDF. For example, some RDF distributors attempt to spread the refuse uniformly over the grate; thus, the air must also be uniformly distributed. Alternatively, some distributors throw the refuse toward the end of the traveling grate, and the refuse is carried to the other end by the grate movement. In this instance, separately controlled underfire air plenums are necessary to ensure proper primary air distribution. Similar to mass-burn systems, a high pressure drop across the grate may aid in the uniformity of air flow through the refuse bed.

Finally, for smaller multistage starved-air combustors, primary air control is not as critical as in larger units. The primary units are small enough that, in general, only the amount of primary air needs to be controlled. Individually controlled underfire air plenums are useful but not necessary. However, uniformity of air flow across the bed is still crucially important and can be accomplished most effectively by high grate pressure drops.

Distribution of Overfire or Secondary Air

The most critical requirement for complete combustion of the unburned material exiting the primary zone is mixing with air before the temperature drops below the level required to destroy the organic intermediates. In almost all current municipal waste combustion designs, secondary air is used to aid the lower furnace mixing. The correct design of the overfire air injection scheme is critical to the prevention of unmixed zones and minimizing the emission of trace organics. With proper overfire air injection schemes, particle carryover can be reduced, the flame height can be controlled, and the furnace gaseous concentrations can be made more uniform.

For any combustor type, the overfire air must be introduced in such a way as to cover the entire furnace flow. Only with complete coverage of the flow can the adequate mixing of the furnace gases be ensured. Mixing is a function of how well the injected overfire air contacts the gases rising from the burning refuse bed. In order for "good" mixing to occur, the overfire air jets must penetrate into the gas flow at well distributed locations and they must entrain as much of the furnace gases as possible within a short distance downstream from the injection location. For mass-burn systems, the normal overfire air configuration involves rows of high velocity air jets on the

front and rear walls. Table 5 and Figure 5 provide a summary of typical overfire air jet designs for large mass-burn systems as provided by manufacturers for new systems. The configurations all use front and rear walls and multiple high velocity jets to completely cover the furnace flow. Refuse-derived-fuel-fired spreader-stoker designs also employ overfire air jets to completely cover the furnace flow. For example, Detroit Stoker systems have OFA jets on all four walls below the height of the fuel distributor, while Combustion Engineering designs use tangentially directed high velocity jets above the distributor level. Again, the intent is to achieve complete coverage of the flow with penetrating high velocity jets.

Current designs of small multistage mass-burn systems and water-cooled rotary combustion units also use overfire air to mix the furnace gases. Again, the design and operating goal is to achieve flow coverage and penetration. However, different overfire air injection schemes can be used because of different furnace configurations and smaller dimensions. Many of these systems employ duct injectors which achieve the coverage and penetration by injecting air at high velocities into the flow or from the center line through smaller multiple holes.

The need for secondary air to completely cover and penetrate the flow implies a number of considerations for the design and operation of the injectors. The injector parameters of importance include:

- Quantity of overfire air
- Number and location of injectors
- Injector velocity
- Injector spacing
- Injection angle

TABLE 5. OVERFIRE AIR JET CONFIGURATIONS FOR LARGE MASS-BURN INCINERATORS

Manufacturer	OFA % of Total Air	OFA Configuration	Jet Velocity and Configuration
Deutsche Babcock (Browning Ferris)	20 - 25	Rows on Front and Rear Walls Side Wall Aspiration	100 m/sec 70% penetration
Steinmueller	40	Rows on Front and Rear Walls at Nose	80 m/sec 600 mm w.g. 80 mm dia.
Von Roll (Signal Resco)	30	Rows on Front and Rear Walls at Nose	50 m/sec 50 mm dia. 1 m separation
Widmer & Ernst (Blount)	30	Front and Rear Walls Interlaced Offset Vortex	80 m/sec 70 mm dia.
Martin (Ogden Martin)	20 - 40	Front and Rear Walls Offset	50 - 100 mm dia. 450 mm w.g.
Detroit Stoker	40	2 Rows Each on Front and Rear Walls	(Data Not Available)
Riley/Takuma	30 - 40	Rows on Front and Rear Walls at 3 Levels	(Data Not Available)
Combustion Engineering-db	20	1 Row Front Wall 2 Rows Rear Wall	High Velocity 750 mm w.g.
Volund	40 - 50	1 Row Side Walls Perforated Ceramic Plates-Side Walls 1 Row Back Wall Controlled Air at Feed and Exit of Rotary Kiln	Varies

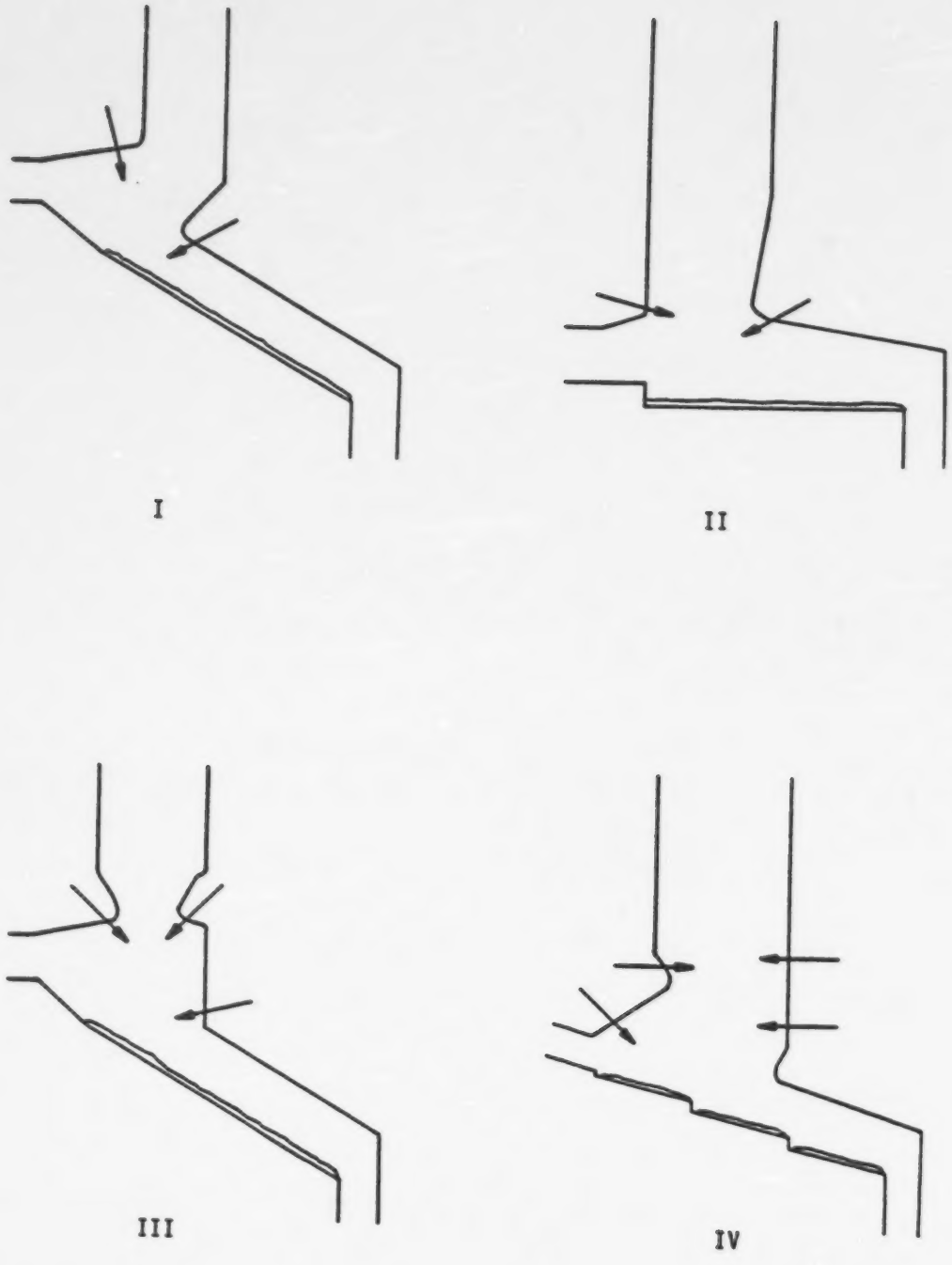

Figure 5. Alternative arrangements for mass-burn overfire air systems.

- Injector shape
- Air supply pressure drop

These parameters are related to each other and to the design of the furnace configuration. The optimum overfire jet configuration would involve numerous high-velocity jets with correspondingly high pressure drops. However, the pumping energy requirements (as indicated by the pressure drop and quantity of air) may become excessive, and the auxiliary power requirements will be too high. Thus, good engineering practice involves achieving penetration and coverage with minimal pumping energy (i.e., low pressure drop). Since the design of the overfire air system may not be exact, it is appropriate to allow for a range of air flow, velocity, and potentially even jet direction in initial hardware design. This would permit on-line optimization to take place. The overfire air design must be tailored to the overall furnace design and operation. The specific requirements for the overfire air injectors are summarized in Table 6 and are described in more detail elsewhere[6].

Verification of Appropriate Air Distribution

The appropriate design of a municipal waste combustor will allow control of the various combustion air streams and will be sufficiently flexible to allow the air to be distributed to the burning regions. An MSW or RDF combustor is a combustion system and thus the various subsystems must be carefully integrated. Recognizing these systems aspects, an important question arises as to how appropriate adjustment of the subsystems can be verified. Current practice involves use of a variety of indicators including:

- Visual inspection
- Exhaust concentration measurements

TABLE 6. REQUIREMENTS FOR OVERFIRE AIR INJECTION IN MWCs

Element	Rationale	Target
Quantity of Secondary Air	Minimum value to contain sufficient momentum to penetrate the furnace flow and maximum value to prevent thermal quench	20-40% of Total Air
Injector Diameter and Velocity	Designed and operated to achieve penetration across furnace and rapid mixing	• Trajectory to achieve 50% penetration before two injector diameters downstream • 90% penetration across furnace
Number of Injectors	Sufficient to achieve furnace coverage	• 100% coverage of furnace flow
Air Pressure	Sufficient to supply velocity to achieve penetration	• Same as for injector diameter and velocity $V\left(\frac{m}{sec}\right) = 20.2\sqrt{\left(\frac{T+460}{520}\right)\Delta P}$ ΔP in w.g. T in °F

- In-furnace probing/mapping experiments

The use of visual inspection is often extremely effective in adjusting air flow distribution (at least coarse distribution). Such visual inspection can be used to guide adjustment of underfire air distribution among the various plenums beneath the grate sections. Exhaust concentrations of oxygen, and CO coupled with visual observation of the flame can be used to adjust overfire air quantity and distribution. Clearly, experimental verification that there are acceptably low exhaust concentrations of the spectrum of PCDDs/PCDFs is proof that the combustor is sufficiently adjusted. To achieve low emission levels almost certainly implies that an appropriate quantity of overfire has been injected and mixed with the effluent from the lower furnace. A number of combustion system designers including Steinmueller/Dravo, Martin systems, and Von Roll have used in-furnace profiling of CO concentration to develop their overfire air injection schemes and to establish an appropriate air flow distribution in particular furnaces. The rationale is that CO concentration is a direct indication of furnace mixing and that peaks in concentration of CO at the fully mixed height are indicators of poor air distribution. The hatched lines representing the 0.1 percent CO profiles in Figure 1 illustrate a relatively flat CO concentration profile at full load and a highly skewed in-furnace CO profile at 60 percent load.

In establishing a new MSW system a combination of the above verifications is required. Visually guided adjustments and exhaust gas measurements are essential components. In-furnace CO profiling may not be necessary for every new unit but is suggested as a diagnostic tool for correcting air distribution in facilities which do not achieve sufficiently low trace organic emission.

If in-furnace profiling is to be performed, the CO measurements must be taken over the entire measurement plane with sufficient spatial resolution to

cover the entire furnace flow. A total of 25-50 sampling locations should be adequate to characterize the profile in any given plane. An in-plane variation in CO concentration greater than 50 percent (e.g., from 1 to 1.5 percent when corrected to the same oxygen concentration level) may be indicative of the need to adjust air flows, although it is essential that this criterion be established more precisely by extensive field testing and engineering analysis. Despite the current lack of precision in this technique, CO concentration profiling can provide an excellent diagnosis of the causes of combustion uniformity.

Combustion Monitoring Requirements

In the previous sections, the goals for design and operation were discussed which would be consistent with proper combustion system operation. In addition to these requirements, the system must be monitored continuously and controlled so that the system functions in the proper operating mode. In other words, continuous monitoring and control is required to help prevent a failure condition. This is particularly challenging when burning the ever-changing supply of refuse which has a relatively low fuel value. Fluctuations in the volatile and moisture content of the refuse must be accounted for properly if the design is to be implemented correctly in practice. If the system is designed properly and tuned accordingly, then the monitoring and control system must ensure only that this system remains within the proper operating envelope.

Three continuous monitoring schemes may be used to ensure that the system stays in compliance:

- Minimum flue gas CO concentration (corrected for O_2 or CO_2 concentration)
- Minimum and maximum levels of flue gas oxygen concentration

- Minimum furnace temperature

These monitoring variables, on their own, are not sufficient to ensure the system is not emitting PCDDs/PCDFs. In particular, they do not provide information on the degree of uniformity within the furnace. This is crucially important to ensuring destruction of intermediates. For example, low exhaust mean CO levels are indicative of the mean conditions, not the isolated pathways which could lead to parts per trillion emissions of PCDD/PCDF species. On the other hand, once the system has been proven to have well-mixed conditions as indicated by low trace organic emissions or by in-furnace profiling or other means, then flue gas CO levels can be used to indicate that no significant change has taken place.

The levels of these monitoring parameters must be specified along with appropriate averaging periods. Discussions with manufacturers of new MSW combustion equipment have provided an indication of the currently achievable level of control and the appropriate target. Currently, many of the manufacturers already use some or all of these measurements for monitoring and control. For CO, it was generally agreed that 100 ppm (corrected to 12 percent CO_2) was achievable. Recent data from mass burn systems have shown that well designed and operated units can achieve low PCDD/PCDF levels from the combustion zone. For example, the new units at Marion County, Tulsa, and Wurzberg and the modified older design, Von Roll facility at Quebec City, Canada, were found to have low PCDD/PCDF and other trace organic emissions over a 4 hour average (sampling time). These same units were found to have rolling average exhaust CO levels of less than 50 ppm over the same averaging period. Thus, this level of CO is proven to be acceptable and achievable with modern design and operating practice.

It has been pointed out that the total combustion air flow should not be too high or too low if the emission of trace organic species is to be minimized. Current practice has recommended that an exhaust O_2 range of between 6 and 12 percent is appropriate. When the proper excess air level has been established for a particular unit, then the control system should operate within a more restrictive range. However, for major corrective action such as a system shutdown, it is appropriate to establish levels outside the 6 to 12 percent range.

Gas-phase furnace temperature monitoring is required to ensure that no low-temperature excursions occur. Measurements in the furnace above the fully mixed height, using suction pyrometry to shield from radiation biases, can indicate that the system is being continuously operated in the same thermal environment. In conjunction with other design and operating procedures which ensure uniformity, this measurement prevents thermal failure modes. The most desirable locations are low in the furnace but pyrometer survivability is low in this region. For this reason an upper furnace location which is related to the fully mixed height temperature of 980°C (1800°F) is a reasonable compromise. Simultaneous measurement at both locations during tune-up would allow the upper-to-lower furnace temperature requirements to be defined in an empirical relationship.

System Control

The final element of a strategy to minimize emissions of trace organics is the control of the combustion system relating to the combustion process. A control system is required in order to maintain a desired steaming rate with changing refuse characteristics. The control schemes used by the various manufacturers are described in Reference 5. Many of the new systems use multiple-loop automatic control schemes which change refuse charging rates,

grate feed rates, and underfire and overfire air flows in response to changes in steam pressure and other monitoring variables such as flue gas oxygen or furnace temperature. The key goal of these automatic control systems is to avoid failure modes while maintaining steaming rate.

In addition to maintenance of steam pressure, the other aspect of control is the system response to excursions in monitored parameters. Specifically, one possible response to a CO excursion or for low temperatures is to initiate auxiliary fuel combustion via an auxiliary burner. These auxiliary burners should burn a clean fossil fuel such as natural gas or light fuel oil with sufficient capacity to rapidly dampen out the results of the excursion. In this manner the inventory of refuse that remains in the furnace at the start of the excursion will be burned under appropriate conditions. A complete halt to refuse feeding should not be necessary unless the excursion persists. However, the feed rate would have to be reduced so that the steam rate does not exceed the desired level.

The other need for auxiliary fuel is for start-up. As previously mentioned, low temperature has been specifically identified as a failure mode. To avoid this failure mode on start-up, auxiliary fuel should be used to raise the furnace temperature to the operating point before waste is added. The capacity of the auxiliary fuel system should be consistent with these needs; current practice suggests that capacity equal to 60 percent of the maximum design heat input is appropriate.

Finally, low load operation is of concern because the combustion conditions may deteriorate as the firing rate is reduced. Lower firing rates may result in lower temperatures and poorer mixing due to slower overfire air injection velocities and lower combustion intensity. A specific load level below which performance is unacceptable has not been established, and is most likely system-specific. In fact, special design and operating procedures can

be developed to extend the range of operation for any particular system. For example, steam jets might be used to supplement overfire air jets during low load operation. Most manufacturers expressed preference for operating above 80 percent but below 110 percent rated capacity. If lower load operation is desired, then additional testing such as in-furnace CO profiling, temperature profiling, or stack emission testing to verify low exhaust organics concentration at the lowest firing rate may be appropriate.

CONCLUSIONS

Strategies for good combustion can minimize the emission of hydrocarbon pollutants from the combustor/boiler subsystem of a waste-to-energy system. These practices will also contribute to the operability of the plant because they will reduce furnace corrosion rates and improve efficiency levels. Thus, while it may not be possible to entirely eliminate trace organic emissions, it should be possible to operate cost-effective, waste-to-energy systems with minimal emissions of potentially toxic organics; i.e., in the fractional parts per trillion emission concentration range.

This study synthesized "best combustion practices" from: theories on the basic mechanisms of PCDD/PCDF formation and destruction in combustion systems, information provided by manufacturers on the design of waste-to-energy systems, and operating/emissions data from specific plants. The practices are designed to:

1. Limit the formation of hydrocarbons
2. Maximize the destruction of these same compounds prior to exiting the combustor/boiler, should they be formed

As such, these practices restrict conditions which promote the formation of hydrocarbons. In addition, they ensure that the environment experienced by

these hydrocarbons will promote the destruction of these compounds. Thus, the conditions within the combustor environment that satisfy these goals are:

- Mixing of fuel and air to minimize the existence of long-lived, fuel-rich pockets of combustion products
- Attainment of sufficiently high temperatures in the presence of oxygen for the destruction of hydrocarbon species
- Prevention of quench zones or low temperature pathways that will allow partially reacted fuel (solid or gaseous) from exiting the combustion chamber.

The development of "best combustion practices" to minimize emissions of trace organics from MWCs involves all of these elements:

- Design. Design the system to satisfy several criteria which will ensure that temperatures and the degree of mixing within the combustor are consistent with the minimization of formation and the maximization of destruction of the species of concern.
- Operation Control. Operate the system in a manner which is consistent with the design goal and provide facility controls which prevent operation outside an established operating envelope.
- Verification. Monitor to ensure that the system is continually operated in accordance with the design goals.

It is suggested that, if all of these elements are satisfied, then the emission of hydrocarbons from the combustor of a MWC will be minimized.

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